A DCCT-Based 100-A DC Current Source With High Stability

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***Abstract* — This paper presents a simple solution to realize a 100-A dc current source with high stability. The new source is based on an improved voltage-controlled current source (VCCS) circuit, and a wideband dc current transducer (DCCT) is added for high-current conversion in the feedback loop. The advantage of this modification is that the power consumption on the sample resistor of the VCCS can be greatly reduced, thus the resistor stability can be easily guaranteed. The preliminary measurement results show that the current stability of the designed source is better than 0.5 ppm/h.**

***Index Terms* — DC current transducer, high-current measurement, high-current source, high-current supply, transconductance amplifier, voltage-controlled current source.**

I. Introduction

The voltage-controlled current source (VCCS) circuit shown in Fig. 1 is a relatively simple solution to realize high-precision dc current sources. Based on the circuit, a 250-mA, 100-W dc current source with stability better than 0.25 ppm/30min has been designed for the Joule Balance Project at the National Institute of Metrology (NIM) of China [1], and a 10-A version with stability better than 0.1 ppm/h has also been presented to evaluate the stability of the ultra-precision high-current meter being developed at NIM [2], [3].

However, to further extend the output current range and keep the stability of the same order of magnitude, these solutions [1]–[3] are not competent. For high-current source, the major limitation of the traditional VCCS circuit shown in Fig. 1 is the stability of the sample resistor R_S. Take this design for example, to realize a 100-A current source with stability better than 1 ppm, the stability of R_S should be better than 0.58 ppm as discussed in [3]. To ensure sufficient signal-to-noise ratio, according to experience, the voltage reference V_{REF} should be greater than 100 mV. Since the output current $I_L = V_{REF} / R_S$ [1]–[3], R_S will be greater than 1 mΩ, which means a power consumption of at least 10 W (remember that this is in the best case). Due to the high power consumption, serious self-heating will be generated and the resistance will drift. As far as we know, a 1-mΩ resistor (or shunt) with stability better than 1 ppm under the current of 100 A is very difficult to realize, and the cost is usually unacceptable.

To solve the problem, this paper presents an improved solution by combining the traditional VCCS circuit and a wideband dc current transducer (DCCT) to realize high-current source with high stability. The circuit principle, design and preliminary results are described.

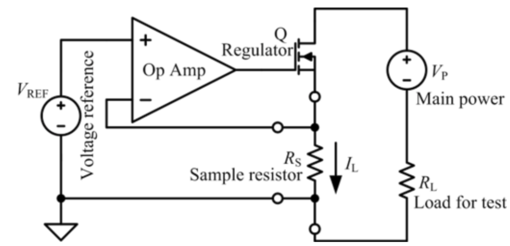

Fig. 1. Traditional voltage-controlled current source circuit to realize high-precision dc current sources [1]–[3].

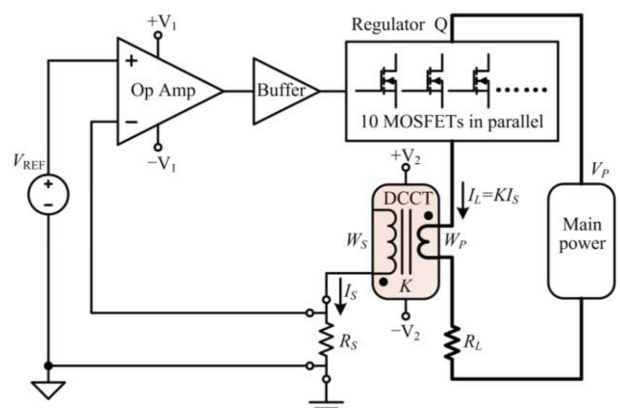

Fig. 2. Functional diagram of the designed 100-A dc current source.

II. Principle

The functional diagram of the designed 100-A dc current source is shown in Fig. 2. Compared with Fig. 1, the major improvement is adding a wideband DCCT in the feedback loop for high-current conversion.

The operation of the circuit can be described as follows. The differential voltage between the reference voltage V_{REF} on the inverting terminal and the voltage drop across the 4-wire sample resistor R_S on the non-inverting terminal of the error amplifier (Op Amp) is amplified to drive the regulator Q to output a current I_L. The current I_L flows through the primary winding of a wideband DCCT with a conversion ratio of K, so the secondary current I_S is $I_S = I_L / K$ and flows through R_S. Then a negative feedback is established.

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Suppose that the Op Amp and the unity gain Buffer are ideal, and the bandwidth of the DCCT is wide enough and has no effect on the loop stability. In normal working condition, attributed to the role of negative feedback, the equation governing the output current I_L can be written as:

$$I_L = \frac{KV_{\mathbf{REF}}}{R_S}, \qquad (1)$$

Equation (1) shows that, compared with Fig. 1, to obtain an identical I_L under the condition of the same V_{REF}, the power consumption on R_S will reduce K times. Thus, the new solution avoids the demand of a small sample resistor with high-power and high-stability.

By taking total differential on both sides of (1), the following equation can be obtained

$$\frac{dI_L}{I_L} = \frac{dV_{\mathbf{REF}}}{V_{\mathbf{REF}}} - \frac{dR_S}{R_S} + \frac{dK}{K}, \qquad (2)$$

where dI_L / I_L, $dV_{\text{REF}} / V_{\text{REF}}$, dR_S / R_S and dK / K are, respectively, the relative change (or stability) of I_L, V_{REF}, R_S and K. Since the signs in (2) only indicate the current change direction rather than magnitude, the stability of I_L will be determined by the stability of V_{REF}, R_S and K.

In practice, however, the equivalent input-noise and drift voltage e_{eq} of the Op Amp cannot be ignored. The effect of e_{eq} can be equivalent to in series with V_{REF} [3]. Thus, when considering e_{eq}, (2) should be

$$\frac{dI_L}{I_L} = \frac{dV_{\mathbf{REF}}}{V_{\mathbf{REF}}} + \frac{de_{\mathbf{eq}}}{V_{\mathbf{REF}}} - \frac{dR_S}{R_S} + \frac{dK}{K}, \qquad (3)$$

where it has been assumed that $e_{\text{eq}} << V_{\text{REF}}$. Since all the items on the right side of the equal sign are not related, the following relationship should be satisfied in practice

$$\frac{dI_L}{I_L} \le \sqrt{\left(\frac{dV_{\mathbf{REF}}}{V_{\mathbf{REF}}}\right)^2 + \left(\frac{de_{\mathbf{eq}}}{V_{\mathbf{REF}}}\right)^2 + \left(\frac{dR_S}{R_S}\right)^2 + \left(\frac{dK}{K}\right)^2}. \qquad (4)$$

In this design, the required current stability is $dI_L / I_L < 1.0\times10^{-6}$. According to (4), there should be

$$\frac{dV_{\mathbf{REF}}}{V_{\mathbf{REF}}} = \frac{de_{\mathbf{eq}}}{V_{\mathbf{REF}}} = \frac{dR_S}{R_S} = \frac{dK}{K} = 5.0\times10^{-7}, \qquad (5)$$

which can be considered as the selection criteria for the key components including the V_{REF}, R_S, Op Amp and DCCT.

III. Design and Test

In this design, V_{REF} = 1 V, R_S = 10 Ω and K = 1000. According to (1), the output current I_L = 100 A. Both the 1-V voltage reference and the 10-Ω sample resistor are specially designed in the lab, and their stability is better than 0.2 ppm. A homemade DCCT with –3 dB bandwidth greater than 100 kHz and ratio stability (under 600 A) better than 0.2 ppm/24h is used for high-current conversion in the feedback loop. The regulator Q is 10 power MOSFETs in parallel mode. The main power V_P is a commercial switch-mode power supply with the maximum output current 125 A and rated power 1500 W. The error amplifier is a selected OP177G. To enhance its capacitive load driving ability, a wideband power buffer with a frequency correction network (not shown in Fig.2) is added.

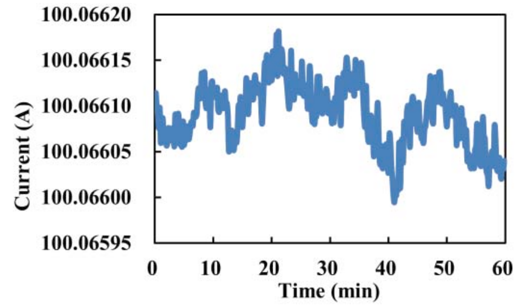

Fig. 3. Measurement results in one hour.

A prototype has been developed in the lab and preliminary results are measured and shown in Fig. 3. It can be seen that the current stability (relative standard deviation) in one hour is about 0.47×10^{-7}. Other important specifications including the accuracy, repeatability and long-term stability are being tested.

IV. Conclusion

A 100-A dc current source with stability better than 0.5 ppm/h has been realized. The new source is based on an improved VCCS circuit with a wideband DCCT for high-current conversion in the feedback loop, thus the power consumption on the sample resistor can be greatly reduced. The new solution can be modified for superconducting magnet to generate homogeneous high magnetic field, and can also be used for evaluating the stability of small resistors (or shunts) in the range of 0.1–10 mΩ.

A programmable high-current source based on the presented solution is being developed in the lab. Further improving the load regulation is the major work in the future.

Acknowledgement

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